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Multi-strange baryon production in pp collisions at $\sqrt{s} = 7$ TeV with ALICE ☆

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ABSTRACT

A measurement of the multi-strange Ξ^- and Ω^- baryons and their antiparticles by the ALICE experiment at the CERN Large Hadron Collider (LHC) is presented for inelastic proton–proton collisions at a centre-of-mass energy of 7 TeV. The transverse momentum (p_T) distributions were studied at mid-rapidity ($|y| < 0.5$) in the range of $0.6 < p_T < 8.5$ GeV/c for Ξ^- and $\overline{\Xi}^+$ baryons, and in the range of $0.8 < p_T < 5$ GeV/c for Ω^- and $\overline{\Omega}^+$. Baryons and antibaryons were measured as separate particles and we find that the baryon to antibaryon ratio of both particle species is consistent with unity over the entire range of the measurement. The statistical precision of the current data has allowed us to measure a difference between the mean p_T of Ξ^- ($\overline{\Xi}^+$) and Ω^- ($\overline{\Omega}^+$). Particle yields, mean p_T, and the spectra in the intermediate p_T range are not well described by the PYTHIA Perugia 2011 tune Monte Carlo event generator, which has been tuned to reproduce the early LHC data. The discrepancy is largest for Ω^- ($\overline{\Omega}^+$). This PYTHIA tune approaches the p_T spectra of Ξ^- and $\overline{\Xi}^+$ baryons below $p_T < 0.85$ GeV/c and describes the Ξ^- and $\overline{\Xi}^+$ spectra above $p_T > 6.0$ GeV/c. We also illustrate the difference between the experimental data and model by comparing the corresponding ratios of $(\Omega^- + \overline{\Omega}^+)/(\Xi^- + \overline{\Xi}^+)$ as a function of transverse mass.

1. Introduction

The multi-strange baryons, Ω^- (sss) and Ξ^- (dss), are particularly important in high energy particle and nuclear physics due to their dominant strange quark (s-quark) content. The initial state colliding projectiles contain no strange valence quark, therefore all particles with non-zero strangeness quantum number are created in the course of the collision. Moreover, the energy of the Large Hadron Collider (LHC) and its high luminosity allow for an abundant production of strange hadrons. These two factors make multi-strange baryons a valuable probe in understanding particle production mechanisms in high energy collisions.

We present a measurement of Ω^- and $\overline{\Omega}^+$ baryon transverse momentum (p_T) spectra and yields in proton–proton (pp) collisions at a centre-of-mass energy ($\sqrt{s}$) of 7 TeV, a measurement of Ξ^- and $\overline{\Xi}^+$ yields and spectra at the same energy, and a comparison of these data to a recent pp event generator, PYTHIA Perugia 2011 central tune (P2011). The measurements were obtained using the ALICE experiment [1] at the LHC.

ALICE is a general purpose detector designed to study both pp and Pb–Pb collisions at TeV-scale energies. A six-layer silicon inner tracking system (ITS) and a large-volume time projection chamber (TPC) enable charged particle reconstruction with excellent momentum and spatial resolution in full azimuth down to p_T of 100 MeV/c.

2. Data sample and cascade reconstruction

Multi-strange baryons are studied in a sample of approximately 130 million minimum bias $\sqrt{s} = 7$ TeV pp events, collected during the 2010 data taking. The sample is corrected for trigger inefficiencies and biases to recover a normalized sample of inelastic (INEL) events, as described in [2]. The events are selected within 10 cm of the detector's centre along the beam direction, with vertex resolution in the transverse plane of a few hundred micrometres. The event vertex range is selected to maximize particle trajectory (track) reconstruction efficiency within the ITS and TPC volume.

Ξ^- and $\overline{\Xi}^+$ ($\Xi^\pm$), as well as Ω^- and $\overline{\Omega}^+$ ($\Omega^\pm$) candidates are reconstructed at mid-rapidity ($|y| < 0.5$) via their characteristic weak decay topology, $\Xi^-(\overline{\Xi}^+) \to \Lambda(\overline{\Lambda}) + \pi^-(\pi^+)$, and $\Omega^-(\overline{\Omega}^+) \to \Lambda(\overline{\Lambda}) + \mathrm{K}^-(\mathrm{K}^+)$, as described in detail in [3]. The branching ratios for these decay channels are 67.8% for $\Omega^\pm$ baryons and 99.9% for $\Xi^\pm$. Charged particles, compatible with kaon, pion and proton hypotheses, are identified using their energy loss in the TPC. The topology of the Ω^- and Ξ^- weak decay is cascade-like and consists of a V-shaped decay of the daughter Λ baryon (Λ baryon hypothesis is identified as a "V0") plus a negatively charged track (h$^-$). The same applies to antibaryons, however in that case the decay products are the $\overline{\Lambda}$ daughter particles and a positively charged track (h$^+$). In general, the acceptance and efficiency depend on both y and p_T. We chose the y interval such that our efficiency and acceptance depend only on p_T. Candidates are selected by placing restrictions on the topology of the

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Table 1
Selection criteria parameters for V0 (Λ) and cascades ($\Xi^{\pm}$ and $\Omega^{\pm}$) presented in this Letter. If a criterion for $\Xi^{\pm}$ and $\Omega^{\pm}$ finding differs, the criterion for $\Omega^{\pm}$ hypothesis is in parentheses. DCA stands for "distance of closest approach," and PV for "primary event vertex." The fiducial volume is defined by the coordinate of the decay vertex position, the transverse radius, R_{2D}. θ is the angle between the momentum vector of the reconstructed V0 or cascade, and the line segment bound by the decay and primary vertices. For cascades, the curvature of the particle's trajectory is neglected.

V0 finding criteria	
DCA ($h^{\pm}$ to PV)	> 0.04 (0.03) cm
DCA (h^- to h^+)	< 1.6 standard deviations
Λ mass (m_{V0})	$1.110 < m_{V0} < 1.122$ GeV/c^2
Fiducial volume (R_{2D})	$1.4 < R_{2D} < 100$ cm
V0 pointing angle	$\cos\theta_{V0} > 0.97$
Cascade finding criteria	
DCA ($\pi^{\pm}$ ($K^{\pm}$) to PV)	> 0.05 cm
DCA (V0 to PV)	> 0.07 cm
DCA ($\pi^{\pm}$ ($K^{\pm}$) to V0)	< 1.6 (1.0) cm
Fiducial volume (R_{2D})	0.8 (0.6) $< R_{2D} < 100$ cm
Cascade pointing angle	$\cos\theta_{casc} > 0.97$

decay. These have been optimized to obtain maximum mass signal significance and are listed in Table 1.

The resulting invariant mass distributions for both species hypotheses are shown in Fig. 1. The signal extraction method is described in detail in [3]. The signal is extracted using a bin-counting method and then corrected for detector efficiency and acceptance using PYTHIA Perugia 0 [4] generated Monte Carlo events propagated through ALICE using GEANT3 [5].

3. Systematic uncertainties

There are two types of systematic uncertainties in the resulting particle spectra: p_T-dependent systematic uncertainties that are due to the efficiency determination and the signal quality at a given p_T, and the p_T-independent uncertainties due to normalization and other factors explained below.

The point-to-point systematic uncertainties vary between 1–4% for $\Xi^{\pm}$, and 1–9% for $\Omega^{\pm}$, with minimum uncertainty found at $p_T = 1.5$–4.0 GeV/c for both species. The p_T-independent systematic uncertainties stem from several sources and reflect the following:

- the uncertainty in determination of the material thickness traversed by the particles (material budget), 4%;
- the use of FLUKA [6,7] to correct [8] the antiproton absorption cross section in GEANT3 [5], 1%;
- the uncertainty in TPC particle identification via energy loss, 1.5%;
- the uncertainty on the track selection in the TPC, through the restriction on the number of TPC pad plane clusters used in particle reconstruction, 3%;
- in the case of $\Omega^{\pm}$, the removal of cascades that fit the $\Xi^{\pm}$ baryon hypothesis, 1%.

The limited p_T-coverage and determination of the total number of inelastic events used for yield normalization lead to an additional uncertainty in the particle yields and mean p_T ($\langle p_T \rangle$) values. The INEL normalization [2] leads to a +7.0% and −3.5% uncertainty on the yield for all measured particles, while the limited p_T coverage causes a 4.5% uncertainty on the $\langle p_T \rangle$ of all species, 5.5% uncertainty on the yield of $\Xi^{\pm}$ baryons, and 6.5% on the yield of $\Omega^{\pm}$. While the systematic uncertainties (both p_T-dependent and p_T-independent) associated with each spectrum point affect the determination of $\langle p_T \rangle$, the systematic uncertainty on the $\langle p_T \rangle$ for all species is dominated by the 4.5% error due to the limited p_T coverage. Similarly, the systematic uncertainty on the yields is dominated by the uncertainties due to low-p_T extrapolation and event normalization.

4. Results

4.1. Corrected p_T spectra and Tsallis fits

The corrected multi-strange baryon yields per p_T bin per unit rapidity ($1/N_{INEL} \times d^2N/dy\,dp_T$) are shown in Fig. 2(a). They span from $p_T = 0.6$ to $p_T = 8.5$ GeV/c in the case of Ξ^- and $\overline{\Xi}^+$ baryons and from $p_T = 0.8$ to $p_T = 5$ GeV/c for Ω^- and $\overline{\Omega}^+$ baryons. The Tsallis function is used for fitting the spectra, as the measured p_T range covers both soft-physics and fragmentation particle production regions. The functional form is shown below:

$$\frac{d^2N}{dy\,dp_T} = \frac{(n-1)(n-2)}{nT[nT + m_0(n-2)]} \times \frac{dN}{dy} \times p_T \times \left(1 + \frac{m_T - m_0}{nT}\right)^{-n}$$

where T, n, and dN/dy (dN/dy representing the particle yield per unit rapidity) are fit parameters, $m_T = \sqrt{m_0^2 + p_T^2}$, and m_0 denotes the particle mass.

The function is grounded in Tsallis statistics [9]; it approximates an exponential component (represented by the T parameter), as well as a power-law dependence for the high-p_T tail. In Table 2,

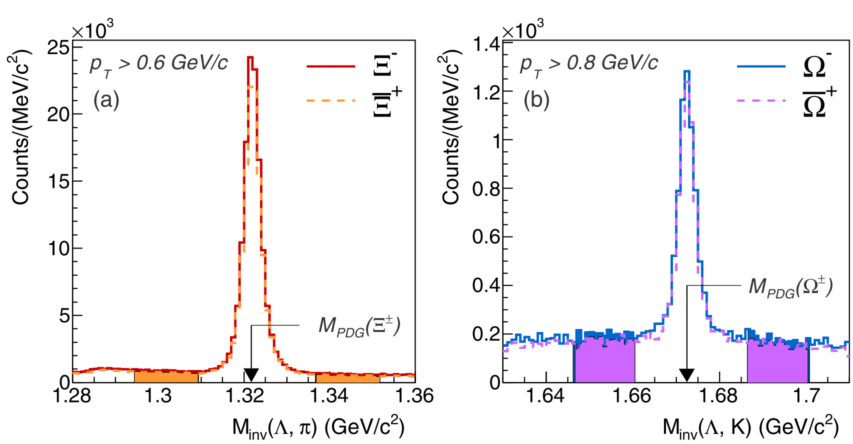

Fig. 1. The invariant mass distributions of Ξ^- (a) and Ω^- (b) baryon candidates (solid histograms) and their antiparticles (dashed histograms). Also marked (in shaded blocks) background sampling regions used in the signal extraction. The entire measured p_T range is presented.

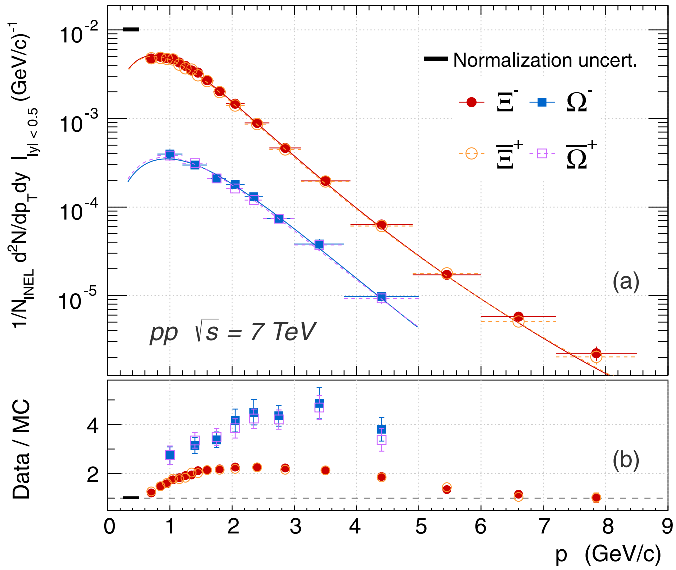

Fig. 2. (a) Ξ^- and Ω^- baryon (solid circles and squares, respectively) and their antiparticle (open symbols) spectra, shown with Tsallis fits. (b) Experimental data to Monte Carlo (PYTHIA Perugia 2011) comparison. The errors are added in quadrature. The normalization uncertainty is shown as a black band.

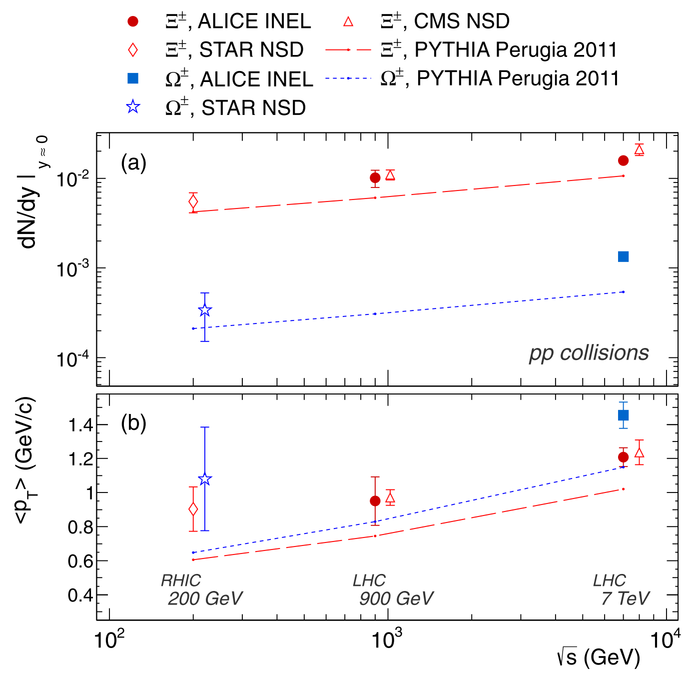

Fig. 3. (a) dN/dy and (b) $\langle p_T\rangle$ of $\Xi^\pm$ and $\Omega^\pm$ as a function of collision energy. The STAR and CMS data are normalized to NSD (see text) events, STAR $\Xi^\pm$ and $\Omega^\pm$ are represented by open rhombuses and stars, respectively. CMS $\Xi^\pm$ measurements are shown as open triangles, and ALICE $\Xi^\pm$ and $\Omega^\pm$ as filled circles and squares. Multi-strange baryons produced using PYTHIA Perugia 2011 simulation ($\Xi^\pm$ baryons as a long-dashed curve and $\Omega^\pm$ baryons as a dashed curve) are plotted for reference. The uncertainties are added in quadrature.

we list the fit results for each particle and antiparticle and the corresponding extrapolated dN/dy and $\langle p_T\rangle$.

The central values of the fit parameters, listed in Table 2, are obtained using the statistical error only. The low-p_T extrapolation of the yield from the Tsallis fit is $\sim 23\%$ for $\Xi^\pm$ and $\sim 26\%$ for $\Omega^\pm$. The value of $\langle p_T\rangle$ for each particle was computed using the fit over the entire p_T range including the extrapolation. The antiparticle to particle ratios were found to be compatible with unity at all p_T.

4.2. Excitation functions

Our measurements of multi-strange baryons can be placed within the broader context of existing pp collision data. We compare to multi-strange baryon yields in pp collisions measured by the STAR Collaboration at $\sqrt{s} = 0.2$ TeV [10], and also to the data obtained by ALICE and CMS at $\sqrt{s} = 0.9$ TeV [3,11]. There are also data from $p\bar{p}$ collisions, obtained by the CDF [12] and UA5 [13] Collaborations. We omit the comparison to these data due to a significantly different kinematic range of the experiments. For STAR, ALICE, and CMS data, an increase in dN/dy as a function of collision energy is observed, presented in Fig. 3(a). We note that the CMS Collaboration used non-single-diffractive events (NSD) to normalize the yield, while in ALICE a normalization to the inelastic events (INEL) was used. For a direct comparison at LHC energies, the INEL $\Xi^\pm$ yield has to be scaled up by 26% to get the yield normalized to NSD events [2]. After scaling, the $\Xi^\pm$ yields per unit of rapidity obtained by ALICE agree with those published by CMS [11]. For Ξ^- baryons and antibaryons, we also observe a slight rise in mean p_T with collision energy, as seen in Fig. 3(b). The $\langle p_T\rangle$ of $\Omega^\pm$ baryons at $\sqrt{s} = 7$ TeV is consistent with 0.2 TeV data, where $\Omega^\pm$ and $\Xi^\pm$ $\langle p_T\rangle$ were consistent within large experimental error. Due to the precision of the current measurements, a significant separation between the $\langle p_T\rangle$ of $\Omega^\pm$ and $\Xi^\pm$ is observed in $\sqrt{s} = 7$ TeV pp collisions.

4.3. $(\Omega^- + \overline{\Omega}^+)/(\Xi^- + \overline{\Xi}^+)$ ratio

The composition of Ξ^- and Ω^- baryons differs only by one valence quark flavour: the d-quark in Ξ^- is replaced by the s-quark in Ω^-. To investigate possible differences in the production mechanism of multi-strange baryons with and without the non-strange quark, we study the ratio of $(\Omega^- + \overline{\Omega}^+)$ to $(\Xi^- + \overline{\Xi}^+)$ baryons as a function of p_T. The dependence on particle mass is reduced by constructing spectra as a function of $(m_T - m_0)$ for each baryon species. To increase the statistical significance of the measurement, for this ratio, the particle and antiparticle spectra are combined. The ratio of the combined spectra, $(\Omega^- + \overline{\Omega}^+)/(\Xi^- + \overline{\Xi}^+)$, is shown in Fig. 4. We observe an increase in the ratio up to $(m_T - m_0) \sim 1.5$ GeV (which corresponds roughly to p_T of 3 GeV/c for either of the baryons), with a possible slope change at a higher $(m_T - m_0)$. The ratio was composed to investigate the possible sat-

Table 2
Tsallis fit parameters, yields, and $\langle p_T\rangle$ for each particle species at $|y| < 0.5$, as well as yields and $\langle p_T\rangle$ extracted from PYTHIA Perugia 2011 [4] simulations. Statistical and then systematic uncertainties for the experimental values are listed. Sufficient statistics were generated to have less than 1% error on all model values.

Particle	T (MeV)	n	χ^2/NDF	$dN/dy \times 10^3$ data	$\langle p_T\rangle$ (GeV/c) data	$dN/dy \times 10^3$ P2011	$\langle p_T\rangle$ (GeV/c) P2011
Ξ^-	$344 \pm 5 \pm 10$	$10.8 \pm 0.4 \pm 0.8$	17.4/15	$8.0 \pm 0.1^{+0.7}_{-0.5}$	$1.21 \pm 0.01 \pm 0.06$	5.38	1.02
$\overline{\Xi}^+$	$339 \pm 5 \pm 9$	$10.4 \pm 0.4 \pm 0.5$	14.4/15	$7.8 \pm 0.1^{+0.7}_{-0.5}$	$1.21 \pm 0.01 \pm 0.06$	5.21	1.02
Ω^-	$460 \pm 40 \pm 60$	$20 \pm 9 \pm 8$	8.8/5	$0.67 \pm 0.03^{+0.08}_{-0.07}$	$1.47 \pm 0.03 \pm 0.09$	0.276	1.14
$\overline{\Omega}^+$	$430 \pm 30 \pm 40$	$14 \pm 5 \pm 6$	7.0/5	$0.68 \pm 0.03^{+0.08}_{-0.06}$	$1.44 \pm 0.03 \pm 0.08$	0.266	1.16

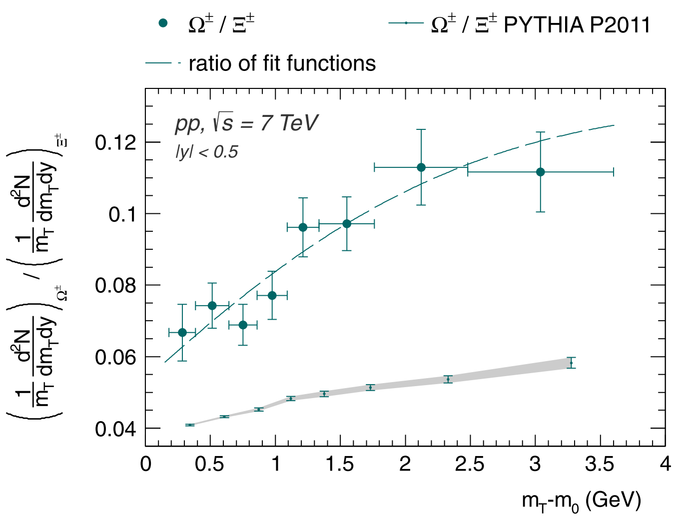

Fig. 4. $(\Omega^- + \overline{\Omega}^+)$ to $(\Xi^- + \overline{\Xi}^+)$ ratio in $\sqrt{s} = 7$ TeV pp events as a function of $(m_T - m_0)$. Experimental data (closed symbols: data points; dashed curve: ratio of Tsallis fits), and PYTHIA Perugia 2011 simulation (solid curve). Errors on experimental points were added in quadrature.

uration of the s-quark production with respect to production of the non-strange quarks, which would be indicated by the flattening of the $(\Omega^- + \overline{\Omega}^+)/(\Xi^- + \overline{\Xi}^+)$ ratio. We found that the currently available data does not allow for a firm conclusion.

4.4. Comparisons to PYTHIA Perugia 2011

The production of strangeness in pp collisions is not well described by the currently available models. In particular, we compare the obtained data to particle spectra from PYTHIA [14], an event generator based on the leading order (LO) perturbative Quantum Chromo-Dynamics (pQCD). PYTHIA is available in different tunes, for example those listed in [4], each reflecting a distinct aspect of particle production inferred from experimental data. Several tunes were tested, among them PYTHIA Z1, Z2 [15], and Perugia 0 [4] tunes. These tunes were several times to an order of magnitude below the measured multi-strange spectra and yields (up to a factor 4 for $\Xi^{\pm}$, 15 for $\Omega^{\pm}$) and thus were abandoned.

In this Letter, we use the central PYTHIA Perugia 2011 (P2011), one of the more recent PYTHIA 6.4 tunes, which describes the 7 TeV pp charged particle spectra reasonably well. P2011 is tuned to the multiplicity and charged particle p_T distributions from 2010 LHC data (as were other tunes tested), utilizes the CTEQ5L parton distribution function, and differs from other PYTHIA tunes by a significant increase in multi-strange baryon yields. This is achieved mainly by removing the baryon suppression inherently present in the built-in "pop corn" meson creation mechanism, but also by tuning the relative u and d vs. s-quark production rates, and adjusting the suppression of the diquark–antiquark hadron production scale [4]. The "pop corn" mechanism, used to describe the hadron production in e^+e^- collisions via chromoelectric flux tubes [16], suppresses baryon production by favouring soft quark–antiquark pairing into mesons [17]. The mechanism was removed in order to approximate more closely the multi-strange yields from LEP experiments [4].

Although the charged-particle multiplicities are reasonably described, as mentioned above, PYTHIA tunes tend to be several times to an order of magnitude below measured multi-strange values. P2011 significantly underestimates multi-strange particle yields, as seen in Table 2, and does not reproduce the spectral shapes of either Ξ^- or Ω^- baryons, with two exceptions. The model describes the high p_T tail of the $\Xi^{\pm}$ distribution and approaches the $\Xi^{\pm}$ distribution below $p_T < 0.85$ GeV/c, as shown in Fig. 2(b).

P2011 also underpredicts $\langle p_T \rangle$ of multi-strange baryons at all energies (Fig. 3(b)), and incorrectly models the increase in dN/dy as a function of centre-of-mass energy (Fig. 3(a)). Indeed, in experimental data dN/dy increases by nearly a factor of three from $\sqrt{s} = 0.2$ TeV collisions to those at $\sqrt{s} = 7$ TeV (factor 35 increase in energy), while P2011 predicts a more modest gain. In both experimental data and P2011, a power-law increase of Ξ^- baryon yield is seen as a function of $\sqrt{s}$. Moreover, P2011 does not reproduce the relative $\Omega^{\pm}/\Xi^{\pm}$ spectral shape, nor the absolute value, although the ratio does increase with increased p_T, as shown in Fig. 4.

5. Conclusions

Our precise measurements of Ξ^-, $\overline{\Xi}^+$, Ω^-, and $\overline{\Omega}^+$ in $\sqrt{s} =$ 7 TeV pp collisions are a benchmark for improving future modelling efforts, including valuable checks on possible hadron production mechanisms, such as the flux-tube mechanism. In addition, the p_T reach of the data to model comparison is the highest ever achieved for multi-strange baryons. The relative production of doubly-strange vs. triply-strange baryons introduces a further constraint on the p_T dependence of particle production from flavour-differentiated quarks. These considerations may enable a better insight into pp collision dynamics, which in turn will serve as a reference for better understanding of fundamental interactions underlying particle creation mechanisms in pp collisions.

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